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IMPACT OF DFIG WINDFARMS AND INSTRUMENT TRANSFORMERS ON TRANSIENT BASED PROTECTION

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Abstract

The impact of wind generation on high frequency, transient-based overhead line protection is investigated. An 8 bus section of the 132kV Scottish network with a realistic DFIG-based wind farm model is simulated on a real time digital simulator. Short circuit studies are conducted on a double circuit overhead line adjacent to the wind farm. Three case studies are compared: the DFIG model, a model with instrument transducers and the control model. Analysis is conducted on frequency and time domain voltage and current waveforms measured at the wind farm bus. These show that, compared with the control case, the impact of each case is slight, but the CVT attenuates the higher frequencies of the voltage waveforms slightly more than the DFIG case.

1 Introduction

Innovation in power system protection has an important role to play in the smart grid revolution. Smart grids must accommodate a more dynamic grid topology with bidirectional power flows, and an uncertain and changing generation mix. Transient based protection (TBP) could meet some of these challenges since it is immune to phenomena based at the power frequency; such as power swings and sub-synchronous resonance associated with compensation equipment. Most importantly, TBP could increase transient system stability and facilitate more power transfer, because of decreased critical clearing times due to extremely fast operating times. One of the few certainties in the future generation mix is an increased penetration of wind generation in order to meet legally binding emissions targets for 2020.

Unlike conventional generation, modern variable speed wind farms use power electronics for power conversion, the most common example being the Doubly Fed Induction Generator (DFIG). A possible concern in the deployment of TBP may be the switching frequencies degrading power quality, leading to deterioration in the performance of local TBP devices. It is therefore important to determine to what extent wind farms affect transient signatures used in TBP.

Novel protection techniques are commonly developed with a much simplified, two bus, power system model. These idealised models fail to capture the transient responses of components elsewhere in the system. Moreover, since high fidelity transient based simulations are computationally demanding they are difficult to execute in real time. Consequently these studies are unable to evaluate the longer term system response of automated control actions including those taken by protective relays. In this study, a section of the UK 132kV network (Fig 1.) is simulated in real time. Two DFIG-based wind farms are modelled along with the local network on a Real Time Digital Simulator (RTDS). The RTDS is a proprietary product from RTDS technologies. Parallel processing is used to accurately simulate a power system of arbitrary complexity in real time at frequencies up to 3kHz.

It would be useful to define at this point what is meant by *transient based protection* [1]. When the power system is subjected to a large step change, such as a short circuit fault, it will undergo a transient period of disturbance. On overhead lines, short circuits result in travelling waves emanating from the fault point and being reflected back and forth from the terminating bus bars. There is much information about the nature of the fault contained in these high frequency signatures. This information can be obtained by filtering or partial (windowed) frequency domain techniques such as the short time fourier transform and the wavelet transform. It can be used to trip circuit breakers by specially designed relays.

2 132kV Primary System

The system modelled forms part of the 132kV network in the Scottish highlands.

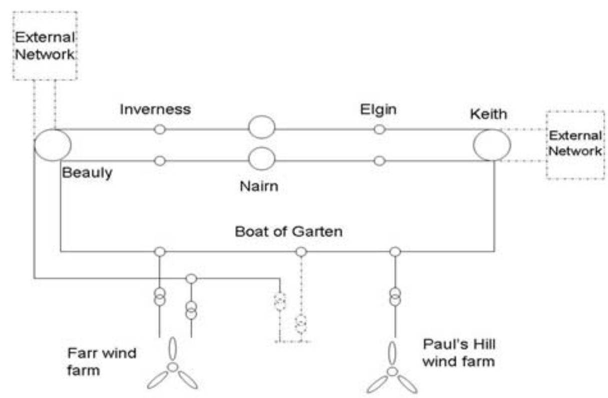

Fig 1: The modelled network can be considered the transmission system for this region.

The system comprises of eight busses arranged in a ring topology (see figure 1). 132kV is the highest voltage level so This area is ideal for this study because it contains two wind farms, that both use Bonus/Siemens 2.3MW DFIG machines. Farr wind farm consists of 40 machines with an installed capacity of 92 MW, and Paul's Hill, connected at the Glen Farclas bus bar, has 28 machines with an installed capacity of 64 MW.

An in-depth discussion of this model is available in [2]. Briefly, sources are represented using the RTDS source model behind the equivalent subtransient impedance. Although strictly speaking, the transient and steady state impedance should also be modelled, the timescales of concern in transient based protection are usually under 0.5 seconds so this approximation should not be too onerous. The over head lines (OHL) are represented using fully frequency dependent, distributed parameter models. Since all but one of the lines are of the double circuit type, it is important to represent the inter-circuit coupling as well as the inter-phase coupling. The RTDS line models were thus 6 conductor, three phase models with accurate placement of the conductors to represent the real world system. The loads were non dynamic and assumed to be purely inductive, modelled using equivalent shunt inductance and resistance. The load flow was specified according to National grid's peak load prediction for winter 2009 available in their seven year statement. The initial conditions are specified but settle down to a steady state after a few seconds of real time operation.

3 DFIG wind modelling

The specific control systems of wind turbines are proprietary to the manufacturer and so cannot be reproduced. The model included here is thus a generic model of a DFIG wind turbine developed by RTDS Technologies. The model's control systems are documented in [3]. The wind farm includes a mechanical model of the turbine, whose input wind speed, pitch and thus mechanical torque can be adjusted in real time. The switching of the valves for both the grid side and the rotor side VSC is decoupled and governed by two separate vector control schemes. This means that on the grid side, frequency can be maintained and real and reactive power can be independently controlled. On the rotor side, maximum energy capture over a wide range of wind speeds is achieved. The model of the partial power converter uses the small time step (below 2μs) VSC component of the RTDS. An interface transformer converts signals from the small time step module to the main power system time step (50μs). This is necessary for the fast switching resolution of the PWM voltage source converters. A discussion of how this is achieved in real time, and the interfacing with the main power system can be found in [4]. Ideally, the wind farm would be modeled using the full number of turbines and the cabled collector system, but this would require considerable processing power to achieve in real time. Therefore, a single turbine model has been scaled up to represent the installed capacity of the entire wind farm and connected at the relevant bus.

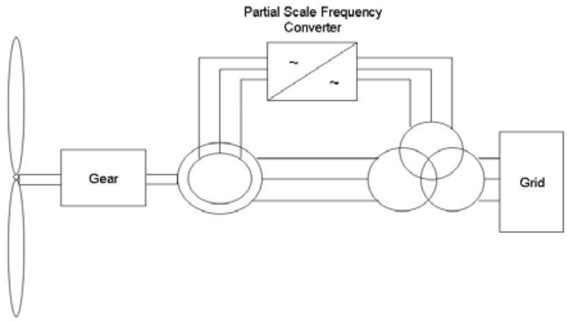

Fig. 2: Basic schematic of a DFIG

4 CVT and CT modelling

A concern with transient based protection is whether instrument transformers will faithfully reproduce the higher frequency system response. It is important therefore to model the CVT and CT with some accuracy, to assess their impact on the operation of transient based relays. The RTDS includes models for a capacitive voltage transformer (CVT) for measuring primary system voltages, and a CT model for system currents.

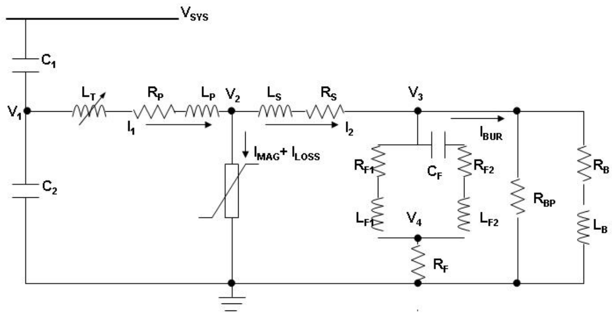

Fig. 3: Equivalent circuit for CVT model

The CVT model comprises of a string of capacitors in series with the primary system that may be adjusted to achieve the desired intermediate voltage V1. The equivalent circuit in figure 3 denotes capacitance C1 and C2. A tuning reactor, $L_{T,}$ is placed at the intermediate bus to compensate the phase angle shift introduced by the capacitors. The intermediate voltage bus is then stepped down by a transformer to provide an acceptable input level, V3, for the relay, usually in the order of 115V_{L-L} RMS. In the RTDS model this transformer includes core hysteresis and saturation effects. A detailed explanation can be found in [5].

The RSCAD component library includes typical values for a 230kV installation. The capacitances C1 and C2 were changed to preserve the value of V1 in the presence of a different primary system voltage. The system voltage and the primary voltage are related by (1).

$$V_1 = V_{SYS} \frac{C_1}{(C1 + C2)} \qquad (1)$$

In the RTDS model, the intermediate voltage V_1 was taken to be 17kV. According to [6] a typical value for the compensating inductor, L_c, is 42H for CVTs rated in the range of 110 – 500 kV. The value of L_c, the sum of C1 and C2, and the system frequency are related in the following way:

$$L_c = \frac{1}{\omega_0^{\ 2}(C1 + C2)} \qquad (2)$$

Solving (1) and (2) for C1 and C2, gives respective values of 0.0538 μF and 0.1874 μF for the capacitors in the voltage divider.

The study CVT's desired output voltage V3, and the intermediate voltage V1, were identical to the conditions in the RTDS test model. It was also assumed that the transformer core saturation characteristics (supplied in the form of points on a B/H curve) would remain the same for a 132kV CVT. These values can be located in [5]

The simple CT model is based on the conductor passing through a toriodal core. The secondary side of the CT is formed by a number of turns around the core. The conductor forms the primary side and effectively is a single turn. The primary side resistance and inductance is negligible so can be ignored. The RTDS model has the following equivalent circuit shown in figure 4.

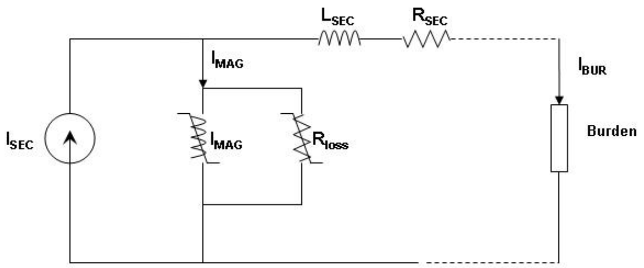

Fig. 4: Equivalent circuit for CT model

The magnetising branch only becomes significant when the CT core begins to reach saturation at the knee point. This may happen under certain transient conditions when large over-currents occur due to a fault. Under such conditions, an increasing amount of current is drawn down the magnetising branch and the current presented to the burden is (4).

$$I_{BUR} = I_{SEC} - I_{MAG} \qquad (4)$$

The RTDS model includes values for a typical installation with 200 turns on the secondary. Since the steady state current of the Beauly-Farr line varies with line loading from about 0.1 – 2kA, this would result in input level to the relay of 0.5-10A, which is reasonable. (Under fault conditions, the relay connected to the CT's secondary side would have to deal with higher overcurrents in the region of 20A. This upper input limit for the relay would depend on the short circuit capacity at either busbar, or, if the core became saturated under certain fault conditions, the knee point of the CT's operating region).

For both the CT and CVT RTDS examples all inductances and capacitances were scaled accordingly to give the same reactance for a 50Hz (rather than 60Hz) power frequency.

5 Methodology

When using transient signatures to affect a trip decision, the most important information is contained within the frequency spectrum immediately following a short circuit fault. The goal of the study was to establish how significant the presence of the wind farms was compared to the transducers. Thus several cases where investigated :

1 Control case: where the wind farms were modelled as equivalent sources and there were no transducers present

2 Instrument transformers: the voltage and current waveforms were obtained via the RTDS CVT and CT models

3 Wind farms: the wind farms at Farr and Paul's hill were modelled with the DFIG model outlined in section 3

From a TBP standpoint, there are further significant power system parameters that affect the transient fault response. These are the fault topology, the fault inception point on the waveform, fault resistance, location of the fault on the line, the power flow through the line and whether the fault is transient or permanent. For each case, seven fault topologies were considered, five with permanent fault resistances of 2ohms and two with variable arc resistance. All the other variables were kept constant with the default case, with the fault occurring at the mid point of the OHL and at voltage maxima on the waveform. Permanent faults were the single phase to ground, phase to phase, phase to phase to ground, three phase and three phase to ground.

Transient faults were modelled with the RTDS fault arc component. This models the variable resistance of an arcing fault according to the arc equation (5) discussed in [2].

$$\frac{dg}{dt} = \frac{1}{\tau}(G - g) \qquad (5)$$

Where g is the time dependant arc conductance, τ is the time constant and G is the stationary arc conductance. In the case of the primary arc, these variables are in turn based on constants that are determined empirically and a fixed arc length. The primary arc length for the single phase to ground fault was assumed to be the distance between the arcing horns 0.5m, and in the phase to phase case the distance between two phases 3.9m. The lower current 'secondary' arc model was not required since the signature under study was pre-circuit breaker. Readings were taken at the Farr bus on the Farr Beauly overhead line. This consists of a 30 km double circuit 132kV line with a single lynx conductor. The geometric tower layout can be found in the appendix of [2]. The CT and CVT waveforms were scaled to match the magnitude of the primary system waveforms.

5 Results

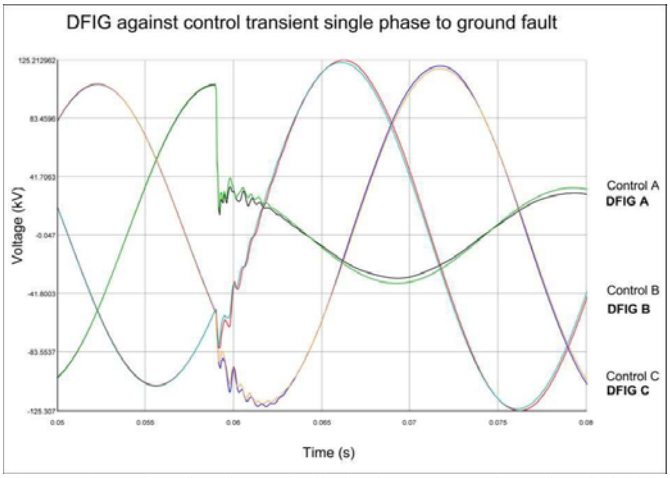

Fig. 4: Voltage time domain graph, single phase to ground transient fault, for DFIG and Control Case

In all cases the transients attenuated in under a quarter of a cycle. This was at voltage maxima fault inception point representing the greatest possible step change. For a transient single phase to ground fault in the time domain the DFIG case shows very little deviation from the control case, see figure 4. This is also the case for a permanent single phase to ground fault, see figure 5. Comparing these two figures indicates difference between arcing and permanent faults on voltage profiles is negligible.

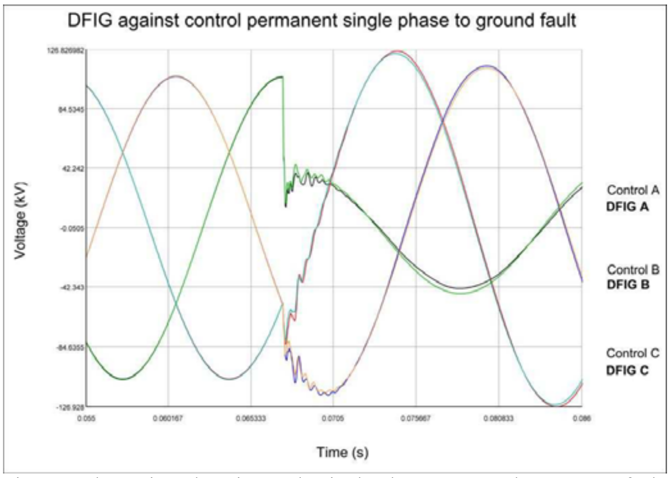

Fig. 5: Voltage time domain graph, single phase to ground permanent fault, for DFIG and Control Case

Figure 6 shows the fault current contribution of the DFIG case is approximately 0.66p.u. compared to the control case. Lower contribution to fault current is a recognised problem with DFIG machines, and has implications for power frequency protection. However, the transients here are very tenuous and cannot be directly compared in the time domain since post fault, the DFIG current is 180 degrees out of phase with the control case. Figure 7 shows that the CVT attenuates the higher frequency voltage perturbations in all phases.

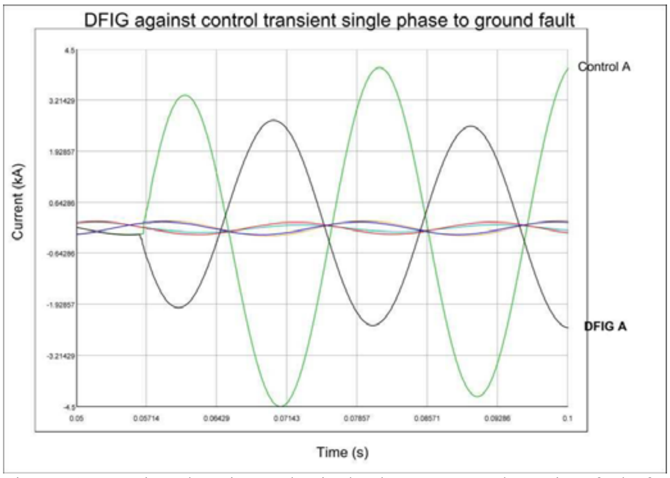

Fig. 6: Current time domain graph, single phase to ground transient fault, for DFIG and Control Case

This is expected as the CVT is inherently capacitive and thus acts as a low pass filter. The effect over the transient period is clearly greater than the DFIG and the control case, indicating that transient based protection robust enough to deal with CVTs could also deal with high penetration of DFIGs.

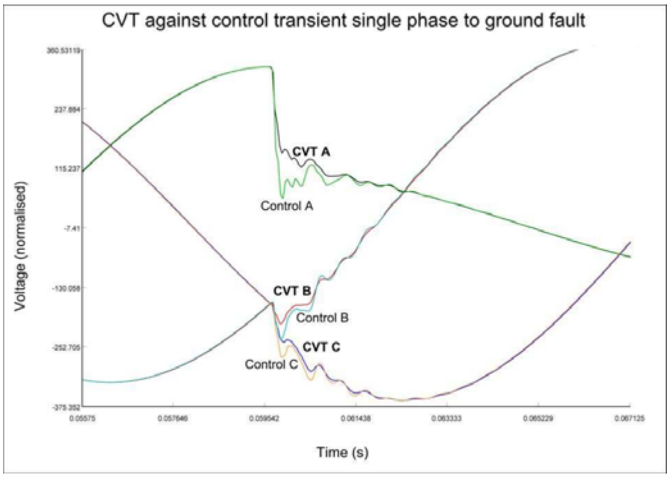

Fig. 7: Voltage time domain graph, single phase to ground transient fault, for CVT and Control Case

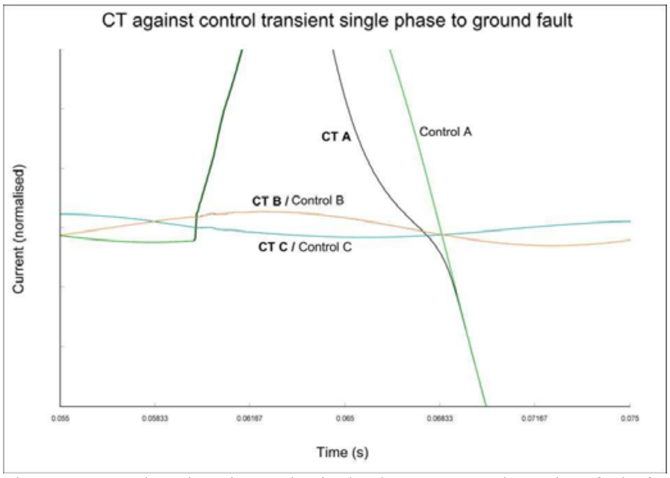

Fig. 8: Current time domain graph, single phase to ground transient fault, for CT and Control Case

Conversely, figure 7 shows the CT follows the high frequency current transients very well. It does become saturated for this high fault current, leading to a distorted faulted phase waveform that does not quite reach the peak with the primary current. (Figure 7 was scaled to show faithful transient CT performance so this lack of peak matching occurs off the scale). This has more significance in conventional power frequency relaying than TBP. The Fourier transforms in Fig 7-9 were compiled for each case for a single phase in a 3 phase to ground fault. Each transform was taken in a window half a cycle pre-fault and one cycle post-fault, and the magnitudes are plotted from 100 – 1000Hz on the same magnitude scale. In the case of the CVT, the time domain was scaled up to match the magnitude of the control waveform before the FFT was taken. Surprisingly, there is little variation in the frequency response of the three cases. The DFIG and the control case showed very similar frequency response, with the DFIG attenuating slightly more towards higher frequencies. As mentioned earlier the CVT acts like a low pass filter, but the cut off frequency of the filter depends on the CVT parameters. Here the CVT attenuates the higher frequencies only slightly more than the other two cases.

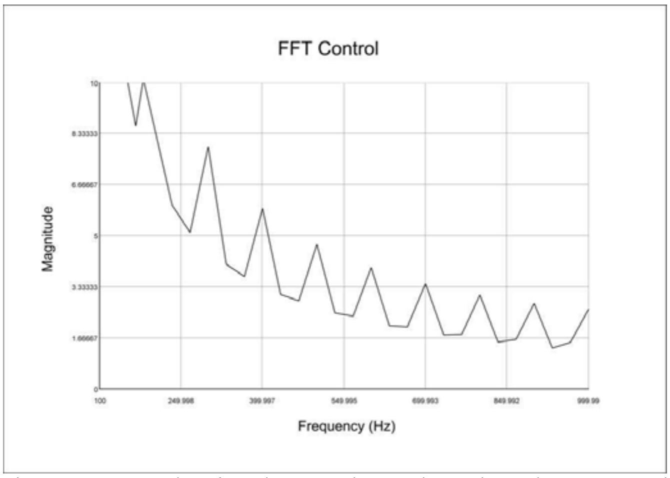

Fig. 7: Frequency domain voltage graph, 0.1-1kHZ, three phase to ground permanent fault, for Control Case

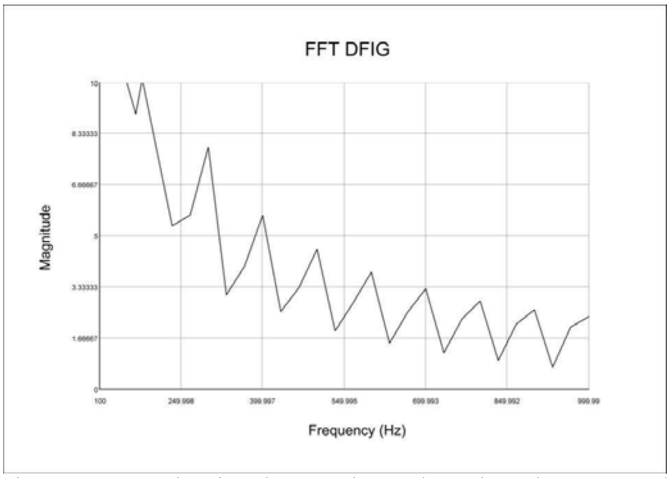

Fig. 8: Frequency domain voltage graph, 0.1-1kHZ, three phase to ground permanent fault, for DFIG Case

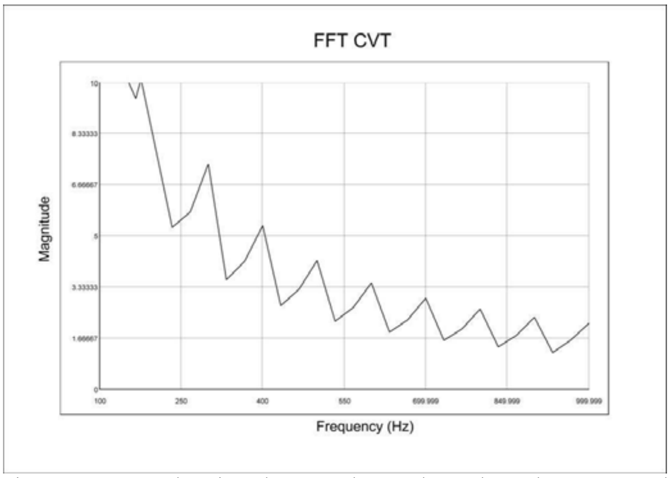

Fig. 9: Frequency domain voltage graph, 0.1-1kHZ, three phase to ground permanent fault, for CVT Case

6 Conclusions

An 8 bus system with wind generation has been simulated on an RTDS and used to investigate transient based non-unit overhead line protection. Very similar frequency responses in the cases bode well for transient based OHL protection. The CVT has more influence than the presence of DFIG wind farms. However, for this relatively short line length the transients attenuated in less than a quarter of a cycle. Sensitive signal processing would therefore be required in detecting this signature and discerning information in real time. This could however be achieved by fast DSP and AI techniques.

Acknowledgements

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